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# A review on methods of flue gas cleaning from combustion of biomass

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ABSTRACT

Application of renewable energy technology is essential for achieving zero carbon buildings within the timescale envisaged by the UK government and the EU because the carbon intensity of the grid will still be high (well above 70% of current level) by 2016 and 2019. The biomass is a key renewable energy source, but its use in buildings is often affected by the emission of particulates and other pollutants in the waste gas, resulting in significant resistant to the technology by building users. The proposed research investigated various ways of removing pollutants, from the exhaust gas of biomass boilers. The review of literature shows that low cost and low maintenance technologies e.g. cyclones are preferred choices however they come with some limitation in removal of particulates. Recent advances in flue gas cleaning came with novel hybrid solutions to overcome traditionally used technologies for flue gas cleaning. Use of electrostatic preceptors with combination of other technologies is one example. The study found that it is difficult to obtain high removal efficiency for smaller particle range and require combination of technologies and improved hybrid solutions.



**Contents**



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## 1. Introduction

Over 80% of fuel delivered to public buildings is used for heating [1]. Most of it comes from non-renewable energy source. The building sector accounts for nearly half of the total energy consumption in UK and so for $CO_2$ emissions as well [2]. There are various means to reduce the emissions and use of biomass is one of them. Biomass is renewable source of energy and produce little net $CO_2$ emissions to the atmosphere.

The biomass boiler is a key renewable energy system for integration with buildings, but its use in buildings is often affected by the emission of particulates and other pollutants in the waste gas, resulting in significant resistant to the technology by building users and owners [3,4]. The relation between rate of death and level of PM10 concentration in the air is being established [4,5]. It is being claimed that long term exposure to PM2.5 may increase 6–8% risk of cardiopulmonary and lung cancer mortality [5]. A certain amount of particulates produced by combustion is released to the atmosphere. Improved techniques to reduce particulate emission are essential for the wider application of biomass boilers, especially as tighter legislation to reduce particulate emission is already proposed for certain areas of England and Scotland. There is a various range of emission sources that contribute to PM10 concentrations in the UK [6]. These sources can be categories as,

- Primary particle emissions which are derived directly from combustion sources, including road traffic, power generation, industrial processes etc.
- Secondary particles which are formed by chemical reactions in the atmosphere, and comprise principally of sulphates and nitrates.

In recent years many advanced flue gas technologies being reported in the literature [7–11] however extensive research work is also being reported in previous decades [12]. The pollutants in the flue gas stream are mainly in two forms gas and particulates [12]. In order to remove toxic gases different types of solvents are used ranging from widely available water to carbon sorbents. However removal of particulates from flue gas stream requires either their deposition or attachment to a surface. These surfaces [12] may be continuous e.g. cone of a cyclone, collection of plates in electrostatic precipitator, or the surface can be discontinuous spray water droplets used in wet scrubber. Removal of particulates generally falls into five main categories; gravity, centrifugal, electrostatic precipitator, fabric, and wet scrubbers. Many advanced level studies on covering different topics of flue gas cleaning methods have been reported in the literature. However, thorough review on flue gas cleaning from the combustion of biomass is lacking in the present literature.

The primary aim of the present research is to thoroughly envisage the existing technologies used in flue gas cleaning from combustion of biomass. Also the comparative performance study in terms of suitability of the technologies for residential building sector will be another highlight. The review paper also provided comprehensive analysis of suitability of different flue gas cleaning options.

## 2. Biomass: a renewable energy source

The capture of solar energy as fixed carbon via photosynthesis is the key initial step in utilising biomass:

$$CO_2 + H_2O + \text{light} + \text{chlorophyll} => CH_2O + O_2 \tag{1}$$

The very important photochemical process as the plants can actually capture and store solar energy. This stored energy can be used as a fuel source. In order to get energy back from the plants; various methods being adopted are combustion [13–15], controlled and un-controlled burning [16–18], digestion [19–22] and many others. In these processes biomass returns the $CO_2$ that was absorbed by the plant in the process of photosynthesis. It is commonly stated that biomass have no net release of $CO_2$ if the cycle of growth and harvest is sustainable. Recent experimental study on sustainable production [23] of switchgrass for bioenergy and feedstock production claimed that early spring harvest may be the best option if the thermochemical processing is the goal. However choice may change if moisture and transportation are other big issues. Sustainable growth and harvest of biomass have many indicators [24] e.g. biodiversity, carbon life cycle, hydrology, soil productivity, etc. and may differ for different types of biomass crops. It is being reported that [25] major barrier for sustainable biomass production for energy in china included technical, financial, policy and institutional.

Biomass is a collective term for all plant and animal material [26]. A number of different forms of biomass can be burned or digested to produce energy. Examples include wood, straw, poultry litter and energy crops such as willow and poplar grown on short rotation coppice and miscanthus. Biomass is a very versatile material and can be used to produce heat (for space and water heating), electricity and a combination of heat and power (electricity). The UK has some of the largest examples of the use of Biomass to generate electricity in Europe [1].

Various sources of biomass are shown in Fig. 1 and also a flow chart (Fig. 2) is given to show the classification of major sources of


**Fig. 1.** Various sources of biomass [modified 26].

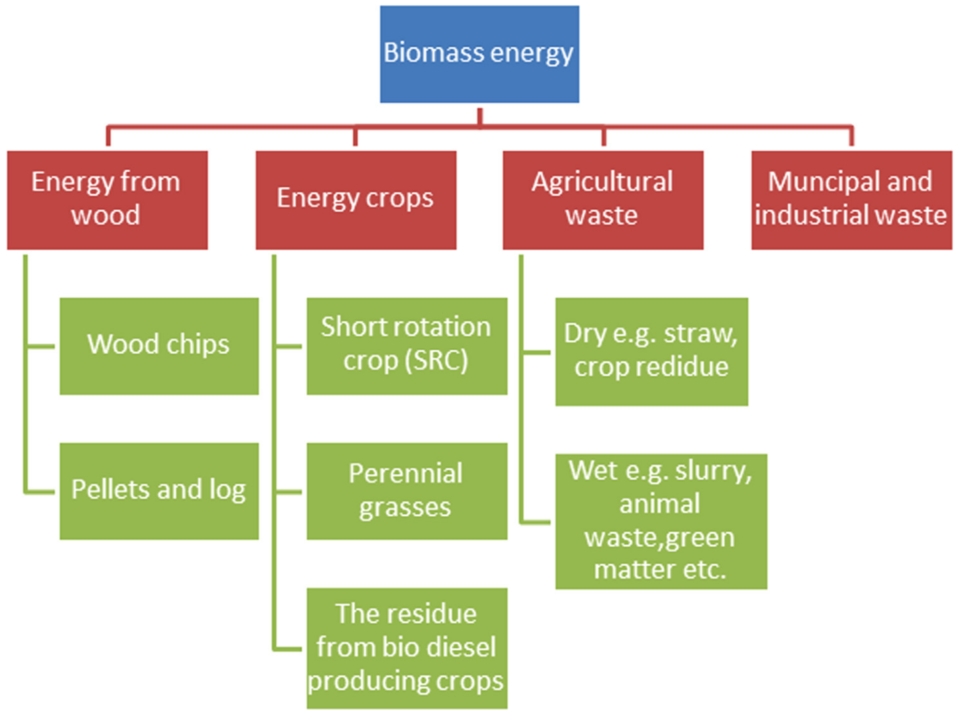


**Fig. 2.** Flow chart for various sources of bioenergy.

**Table 1**
Emissions factor from electricity generation [26–28].

| Emission species | Switch grass (g/Kg) | Poultry litter (g/kWh) | Forestry residues (g/kWh) | Animal slurry (g/kWh) |
|---|---|---|---|---|
| $CO_2$ | 1525 | 10 | 24 | 31 |
| $N_2O$ | 0.09 | – | – | – |
| $CH_4$ | 0.14 | – | – | – |
| $SO_x$ | 0.10 | – | – | – |
| CO | 4.12 | – | – | – |
| $SO_2$ | – | 2.42 | 0.06 | 1.12 |
| $NO_x$ | – | 3.90 | 0.57 | 2.38 |

**Table 2**
Some major sources and associated emissions of biomass.

| Type of biomass | Source | Humidity | Density | Combustion efficiency | Geometry | Emissions | Benefits |
|---|---|---|---|---|---|---|---|
| Wood pellets | Compacted sawdust by product of sawmilling | Low humidity ( < 10%) | High density | Very high | Regular | $NO_x$, $SO_x$, particulate matter and volatile organic compounds, PM | Compact storage |
| Wood chips | Wood, recycled wood, sawmill residue, stem wood, logging residue, etc | Medium ( < 50%) | Low | Medium | Irregular | $NO_x$, $SO_x$, particulate matter and volatile organic compounds, PM | Can be densified into pellets |
| Straw | Dry stalks of cereal plants e.g. oats, rice, eye, wheat etc. | Low (0–30%) [31] | Low | High | Irregular | Polycyclic aromatic hydrocarbons, CO[29], $NO_x$, $SO_x$ [30], volatile organic compounds (VOCs) [31], PM | Can be densified into pellets |

biomass. Biomass is zero carbon and renewable source of energy having low content of C, S, and N and high concentration of volatile matters e.g. Mg, O, P and Ca. They are also low in cost as many biomass resources are bi-product of certain industrial or agriclutural activity. Inspite of having all these benefits these resources have some major issues which always reduce their usability. Low energy density, odour, storage space, and health-safety issues are very important.

Biomass mainly comes from energy crops, wood from trees, agricultural waste, municipal and industrial waste. A classification flow chart is presented here to give an idea of some major resources of biomass. The properties of different kind of biomass coming from different resources also vary widely in terms of moisture content, energy content, density, combustion efficiency, and emissions. But they do have many similarities as well. Gaseous emissions factors from various sources of biomass (Table 1)

**Table 3.1**
Objectives included in the air quality regulations for the purpose of local air quality management[a].

| Pollutant | Air quality objective | |
|---|---|---|
| | Concentration | Measures as |
| **Benzene** | | |
| All authorities | 16.25 μg/m$^3$ | Running annual mean |
| All authorities in England and Wales only | 5 μg/m$^3$ | Annual mean |
| Authorities in Scotland and Northern Ireland only | 3.25 μg/m$^3$ | Running annual mean |
| **1,3 Butadlene** | 2.25 μg/m$^3$ | Running annual mean |
| **Carbon monoxide** | | |
| Authorities in England, Wales and Northern Ireland only | 10 μg/m$^3$ | Maximum daily running 8-h mean |
| Authorities in Scotland only | 10 μg/m$^3$ | Running 8-h mean |
| **Lead** | 0.5 μg/m$^3$ | Annual mean |
| | 0.25 μg/m$^3$ | Annual mean |
| **Nitrogen dioxide** | 200 μg/m$^3$ not to be exceeded more than 18 times a year | 1 h mean |
| | 40 μg/m$^3$ | Annual mean |
| **Particles (PM10) (gravimetric[a])[b]** | 50 μg/m$^3$not to be exceeded more than 35 times a year | 24 h mean |
| **All authorities** | 40 μg/m$^3$ | annual mean |
| Authorities in Scotland only1fnc;[c] | 50 μg/m$^3$ not to be exceeded more than 7 times a year | 24 h mean |
| | 18 μg/m$^3$ | annual mean |
| Sulphur dioxide | 350 μg/m$^3$ not to be exceeded more than 24 times a year | 1 h mean |
| | 125 μg/m$^3$ not to be exceeded more than 3 times a year | 24 h mean |
| | 266 μg/m$^3$ not to be exceeded more than 35 times a year | 15 h mean |

[a] *Source*: http://www.airquality.co.uk/standards.php.
[b] Measured using the European gravimetric transfer sampler or equivalent.
[c] These 2010 air quality objectives for PM10 apply in Scotland only, as set out in the Air Quality (Scotland) Amendment Regulations 2002.

**Table 3.2**
Proposed new PM2.5 objectives (not included in regulations).

| Region | Air quality objective | | Date to be achieved[a] |
|---|---|---|---|
| | Concentration | Measured as | |
| UK (except Scotland)2fna;[a] | 25 μg/m$^3$ | Annual mean | 2020 |
| Scotland2fna;[a] | 12 μg/m$^3$ | Annual mean | 2020 |
| UK urban areas | Target of 15 % reduction in concentrations at urban background locations | 3-year mean | Between 2010 and 2020 |

[a] The concentration cap is to be seen in conjunction with the 15% exposure reduction target.

implicate that $CO_2$ is one of the major contributor in the emission spectrum. Properties of some of the major biomass resources are given in Table 2.

## 3. EU legislations and directives

Biomass boilers could, potentially, be a significant source of emissions. Hence, concern has been raised within the air pollution community at the possible widespread adoption of biomass boilers, especially when these are located in urban areas. The Clean Air Act already regulates emissions from commercial and domestic premises in designated Smoke Control Areas. However, this legislation was developed in the 1960s and is primarily aimed at coal combustion and not appropriate to the modern pollution situation and control of particulate matter emissions from biomass boilers of fractions PM10 and below. The specific concern is that the majority of boilers in urban areas are now gas fuelled, and hence boiler emissions are significantly lower than the Act's requirements. Therefore, although biomass boilers may meet Clean Air Act standards, in many circumstances they still have the potential to produce PM10 emissions that are worser than the current gas equivalent. In addition, under the Environment Act 2005, Local Authorities throughout the UK have a statutory duty to review and assess air quality in their Council area and identify any likely exceedences of the Air Quality Objectives [6]. All Authorities must assess air quality in their area against the objectives set for $NO_2$, PM10 and $SO_2$ (and other gases). At present there is no requirement for Authorities to assess against the PM2.5 Objective. This is to be handled at a national level. The Air Quality Objectives for PM10 and PM2.5 that apply in UK [6] can be found in Table 3.1.

**Table 3.3**
Comparison of emission limit values in different countries [32,33].

| Country | Annual limit value (μg/m$^3$) | 24 h limit value (μg/m$^3$) | Allowance for 24 h limit value |
|---|---|---|---|
| EC till1.6.10 | 40 | 50 | 35 Exceedances p.a. (Austria 30) |
| EC from1.6.10 | 20 | 50 | 35 Exceedances p.a. (Austria 25) |
| Switzerland | 20 | 50 | 1 Exceedances p.a. |
| Norway | 35 | 50 | |
| WHO (AQG) | 20 | 50 | |
| WHO (AQG) | 10 | 25 | |
| USA PM10 | | 150 | 1 Exceedances p.a. on average over 3a |
| USA PM2.5 | 15 | 65 | 98% For average over 3a |

The UK Government and the Devolved Administrations have set new national air quality objectives for particulate matter smaller than 2.5 μm diameter (PM2.5) which is set out in Table 3.2. These objectives have not been incorporated into LAQM Regulations, and authorities have no statutory obligation to review and assess air quality against them [6]. However, it is recognised

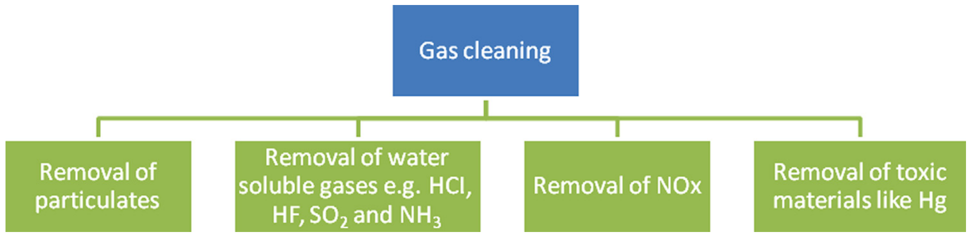


**Fig. 3.** Classification for flue gas cleaning.

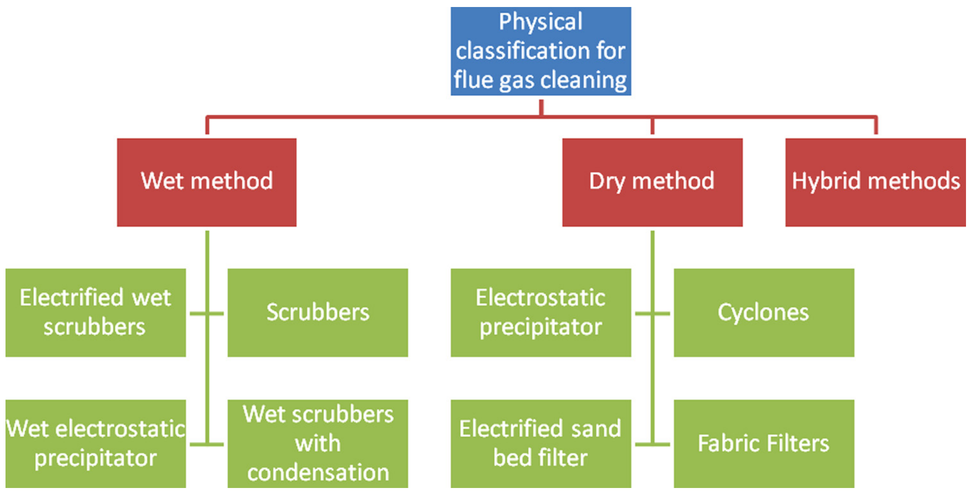


**Fig. 4.** Physical classification of flue gas cleaning methods.

that many authorities are currently undertaking monitoring for PM2.5.

Table 3.3 shows a comparison of emission limit values in different countries. The European Community has set in directives 1999/30/EC and 96/62/EC limits for PM10 in the air. On January 1st, 2005 these standards became effective. In a first phase the limit of the yearly average is 40 μg/m$^3$ and for daily average (24 h mean) 50 μg/m$^3$. The daily average is not allowed to be exceeded more than 35 times per year. In a second phase starting June 1st, 2010 the yearly average standard will be 20 μg/m$^3$ and the daily average limit 50 μg/m$^3$ where as the allowed number of daily exceedances will be reduced to 7 days per year.

## 4. Flue gases and particulate from biomass combustion

The flue gas arising from combustion of biomass can be wet or dry depending on moisture content of biomass fuel used. Also the composition of flue gas varies mainly because of the type of biomass fuel and method of combustion adopted. Flue gas mainly has two parts, particulate matters and toxic gases. Some of the contamination in flue gas is water or some other chemical solvable but there is also possibility that few toxic contaminations are not solvable and need further treatment. Ghafghazi et al. [34] presented detailed study on wood fuel properties, combustion condition, and flue gas cleaning system. Direct measurements of particulate matter emissions from wood boilers with district heating applications are reviewed and presented in the manuscript [34].

## 5. Flue gas cleaning

Though flue gas cleaning systems are designed to clean specific pollutant but sometimes bigger systems can do the whole gas cleaning. Flue gas cleaning consists of removal of particulates, water soluble emissions, removal of $NO_x$ and toxic materials (Fig. 3). Various gas cleaning systems are classified in Fig. 4. Many gases cleaning system can be summarised as removal of particulates, removal of water soluble gases and pollutants,

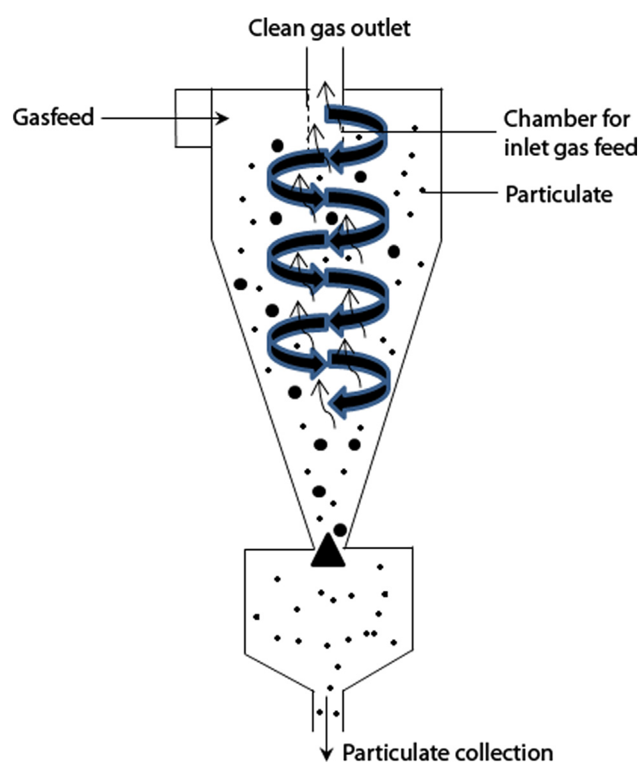


**Fig. 5.** Schematic of typical cyclone system used in cleaning of flue gases.

removal of $NO_x$ and removal of toxic and hazardous pollutants like mercury (Hg).

A particular concern for biomass combustion is the emission of particulates (e.g., PM10 and PM2.5). Particle removal from flue gas can be divided into two main categories (i) dry methods and (ii) wet methods. Dry methods include cyclones [35–37], dry electrostatic precipitator (DESP) [12,38], fabric filters and electrified gravel (sand) bed filter [39–44]. The main wet systems for particulate removal are electrostatic precipitators (WESP) [45–47], electrified wet scrubber (EWS) and scrubbers [48,49] and others.

### 5.1. Dry methods

In dry removal methods for flue gas cleaning no liquid is used, method is either based on inertia principle e.g. cyclones, electro properties of flue gas component electrostatic precipitators, filters based on permeability principles and others. Among many available methods some of the dry methods currently in use for flue gas cleaning would be discussed in this section as follows.

#### 5.1.1. Cyclones

Mainly cyclones are solid–gas separation systems widely used in different industries for cleaning of the waste gas/flue gas. Sometimes cyclones are also used as primary system to reduce the burden on expensive secondary system used for further cleaning in order to comply with regulations [49]. Lee et al. [49] also stated that cyclones have been very useful as pre-cleaning devices of particles larger than 10 μm aerodynamic diameter. At high temperature and pressure working of cyclones is more efficient even for fine particle size of 2–3 μm in diameter, which makes them more economical for use in process industries [50,51]. A basic schematic diagram of cyclone is shown in Fig. 5. Mainly cyclones are dependent on mass of the particle for their removal. Flue gas along containing particulates is feed into a cylinder tangentially in order to achieve rotational movement (Fig. 5). The developed centrifugal forces carry the particles towards the wall of cylinder to the vortex and then finally into particulate collection box. Mostly cyclones are characterised by the particle cut diameter.

It is possible for high efficiency cyclones to achieve collection efficiency up to 70% for particles of 5 μm size, however the collection efficiency decreases rapidly when size of pollutant particles reduces further [49,52–54]. Salcedo et al. [51] presented theoretical development and experimental validation of optimised recirculating reverse-flow gas cyclones. Authors [51] used modified finite diffusive model, consisting of partial recirculation of the cyclones emissions. A high collection of submicron particles is being observed even for lower inlet concentrations (as low as 100 $\mu g/m^3$).

#### 5.1.2. Electrostatic precipitator

Electrostatic precipitators (ESPs) are particle control device utilising the electrical forces to move particulates out of the exhaust gas stream (Fig. 6). The pollutant particles are given an electric charge, which led them to pass through a region where gaseous ion flows called as corona. The electrical field provided to particulates comes from electrodes mounted on surface of the wall and maintain a high voltage in the centre of corona [12]. Electrostatic precipitators (ESPs) are extensively used as capable pollutant control systems. Their major merits of high collection efficiency

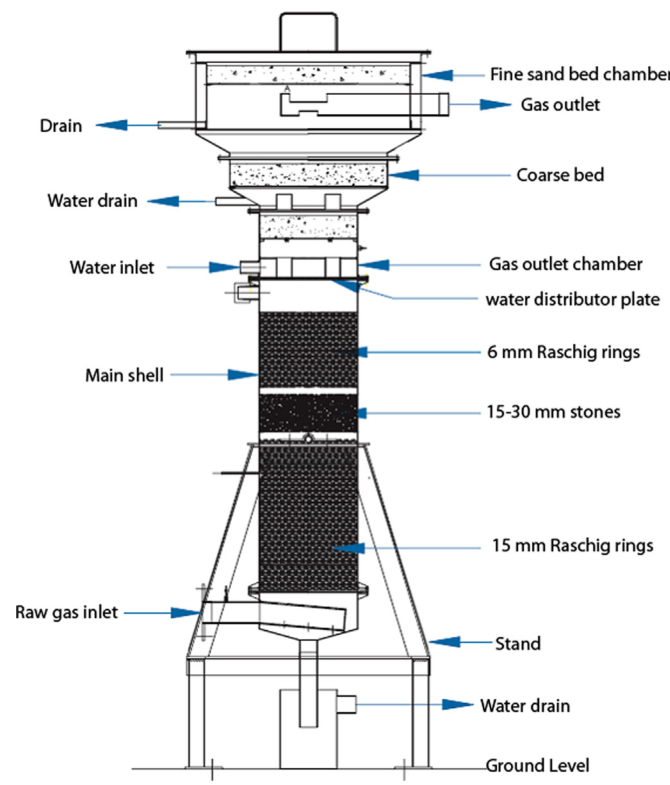


**Fig. 7.** Schematic drawing of wet packed scrubber [48].

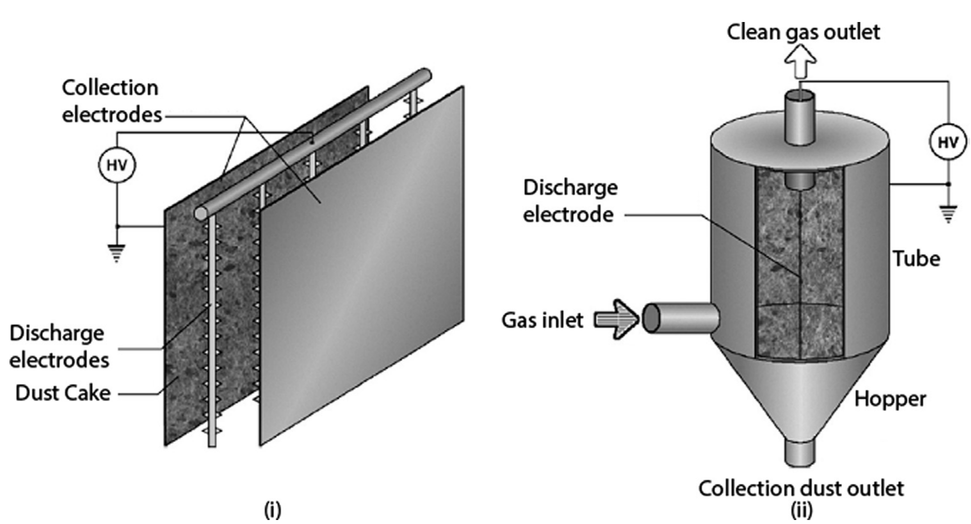


**Fig. 6.** Two types of electrostatic precipitator: (i) parallel-plate and (ii) tubular [60].

and wide range of operating temperature [38,55,56] makes them appropriate solution for various applications in industry. In ESP unipolar charged particles are accelerated by an external applied field, which helps in further increase in collection efficiency [57]. In ESP technology one major problem comes from flue gas having high concentration of chlorides, which produces fine dust with relatively very high resistivity and consequently performance of ESP [58–63]. Especially in combustion of biomass if unwashed straw is used, this problem of high resistivity dominates. There are many types of ESPs having improved functionality are reported in literature e.g. single stage, multi stage, ESP agglomerators, ESP with modified electrode and many others.

#### 5.1.3. Filters

Recently increased tightening in emission limits requires systems and technologies with high efficiency and fabric filter is one of them. However fabric filters have not been very widely used in removal of particulates from biomass combustion. One of the major advantage of this technology is that high removal effieicny of particulate is almost independent of size distribution of particulates in flue gas. Fabric filter is very successful option used where not only particulates but gaseous impurities e.g. $SO_2$, HCl, etc. need to be removed. However one major limitation of fabric filter is that flue gas must be dry otherwise particulate cannot be removed properly from gas. Many modified filters are reported in the literature e.g. electrified sand bed filter, electrets filters, electrically energised fibrous filter, electrically energised granular-bed filters etc. These electrically charged filters claim to achieve removal efficiency of up to 99.97% [64–66].

### 5.2. Wet methods

In wet methods of flue gas cleaning, liquid is used as an agent to extract the contaminants or pollutants from flue gas. Also many gaseous contaminants are water/liquid agent soluble and use that property for removal. Major disadvantage of such types of system lies in the recycling of the collected contaminated liquid used for cleaning of the flue gas. This provides another major challenge to reduce the quantity of liquid used for cleaning purpose. Many wet methods used for cleaning in biomass boiler e.g. scrubbers, electrified wet scrubbers, wet scrubbers with condensation, wet electrostatic precipitator and mop fan. Though mop fan have not been widely used yet. Wet packed bed scrubber can also be used as the cooling–cleaning system in biomass gasifier [48].

#### 5.2.1. Scrubbers

Wet scrubbers have been one of the widely used technology for removal of particulates, acidic gasses, and mist from flue gas. Also a scrubber does not require very complicated design and is easily maintained. Wet scrubbers have been popularly used for the

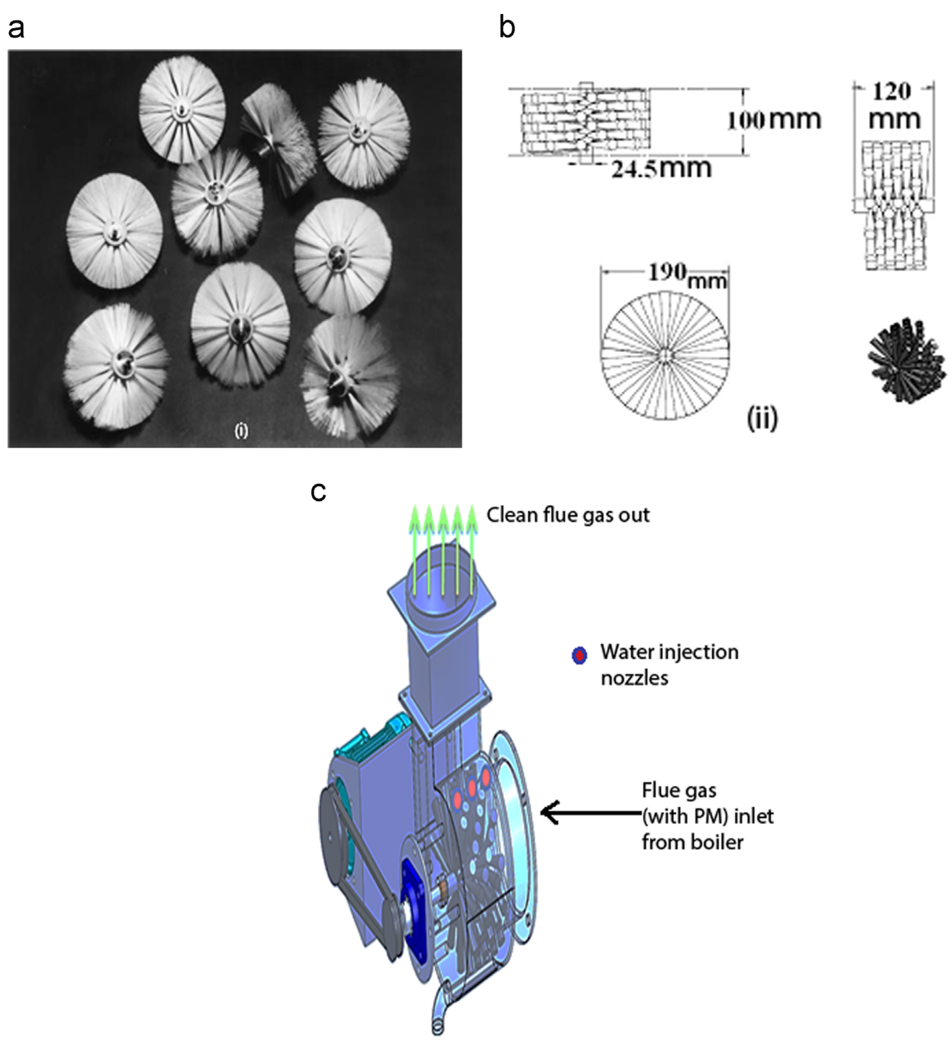


**Fig. 8.** Design of proposed mop fan gas cleaning device: (a) different types of MOP fan, (b) mop fan design used in biomass exhaust gas cleaning and (c) proposed design of small scale biomass boiler with MOP fan [81].

collection of acidic gases, mists, and particles with significantly reducing risks of fire, explosion and erosion [48,67–69]. Many wet scrubbers operate around the water dew point of the exhaust gas from biomass combustion. One major disadvantage in wet scrubber is water pollution and foul smell due to deposition of salt as water is frequently used as scrubbing agent [70] and associated cost in treating the sludge before disposal [71,72]. Another problem because of water as scrubbing agent normally happens in cold climates due to freezing.

Fig. 7 shows wet packed bed scrubber used in cleaning and cooling the exhaust from biomass gasifier utilising 6–7 l of water per minute for a 20 kW gasifier system. In the system dry sand is used as demister.

It is being reported by the authors [48] that unit provided clean gas below the limit of 150 mg/nm$^3$. In a similar study [48] researcher reported tar removal up to 90% is easily achievable. There are some other types of scrubbers also used in cleaning of the gas e.g. venture scrubbers, nozzle scrubber, wet electrostatic scrubbers, wet scrubbers with condensation [73,74] and others.

In electrostatic wet scrubber [74] electric charging of water sprays is done by using electrostatic nozzles. The authors [74] measured efficiency curves and compared two cases; with and without charging the water particles. Authors reported that when particles and water spray are charged with opposite polarity they had given the best results. It is being claimed that cut size of scrubber is reduced upto 0.25 μm from 2.5 μm when particles and water spray is charged. Another study reported [75] that the best results are achieved when particles are charged negative whereas spray positively.

#### 5.2.2. Wet electrostatic precipitator

Wet electrostatic precipitator also known as WESP are claimed to be one of the most effective separators of particulates. One major benefit about them with comparison to ESP is that dust resistivity does not play major role in WESP. In WESP the dust is absorbed in liquid and drained off from the collecting plates. This advantageous feature of WESP enables them to design for high level of dust removal efficiency. In many WESP membranes collection electrodes are used [76,77]. These electrodes are made from soft membranes from materials like silica and carbon fibres. These membrane electrodes let the water spread more uniformly on fibres utilising the capillary force, which lead to high efficiency by reduction in water usages and un-interrupted electric field (as no dust resistivity).

#### 5.2.3. Mop fan

Mop fan is previously being used for air cleaning and other purposes [78–80]. Shukla et al. [81] presented a novel design of mop fan for exhaust gas cleaning. Figures show the proposed mop fan unit (Fig. 8). It is being reported that

- The proposed mop fan has very low capital and operational costs.
- The mop fan is very efficient in removing fine particulates and water soluble chemicals.
- Compared with conventional scrubbers, the mop fan uses much lower volumes of scrubbing liquids (water-based solutions) and hence significantly reduces the cost of waste water treatment.

A centrifugal fan with a low electricity requirement is used to drive the flexi fibre mop. The dirty exhaust gas from the boiler passes through the inlet duct to the centrifugal fan where particulates are trapped by the flexible mop fibres. Water as absorbent is also sprayed into the mop fibres which further enhances the capture of fine particles and absorbs chlorides, ammonia, sulphur compounds and other soluble chemicals. The used water-based absorbent, which contains trapped particulates and soluble chemicals, accumulates at the bottom of fan casing. Accumulated waste can be discharged after certain interval of times. In-line particulate filters in the water-based recirculation circuit are used to prevent trapped particulates re-entering the gas stream. Cleaned exhaust gas leaves the centrifugal fan via the exit duct. It is being reported that exhaust gas cleaning using a mop fan has a significant advantage over conventional liquid scrubbers in terms of waste water treatment cost. The large surface area provided by the mop fibres ensures high removal efficiency for particles and chemicals, and the use of a smaller quantity of water-based solvents results in less waste water requiring treatment before disposal.

### 5.3. Hybrid method

The various techniques discussed in previous sections have some major advantages and disadvantages. Researchers working in the field of flue gas cleaning proposed some hybrid solution which details with innovative and combined principle of more than one technological principle.

#### 5.3.1. Electrocyclone

In general cyclones use the principle of centrifugal force as discussed in previous section to collect the particulates into dust chambers. However there is problem with conventional cyclones which can be used for collection of particulates larger than few microns, as fine particles centrifugal force is lower and collection effieicny is not high. The use of electrical forces (Fig. 9) can solve the problem, when an electrode can be placed in the axis of the cyclone and device is known as electrocyclone [56]. Many studied being reported for electrocyclone [69,82–85] and used different methods for supplying powers e.g. dc power source, pulsed voltage excitation and high voltage electrode charge. However collection effieicny reduces significantly when flow rate is too high.

#### 5.3.2. Novel swirl cyclone

Lee et al. [49] proposed a novel swirl cyclone given in figure below (Fig. 10). Authors claimed that [49] conventional cyclones are not very efficient in removal of smaller particle size and wet particle removal methods have problems of blockage, foul smell and salt formation. Proposed novel swirl cyclone consists of cyclone, swirl scrubber with cone and plates. In the present novel swirl cyclone increased efficiency of collection of PM10 is achieved by the scrubbing effect. The novel system consists of [49] cyclone, swirl plates, scrubber, a feeding mechanism, scrubbing medium, demister and a circulation device. Gas stream first pass through the cyclone zone, it goes to swirl plate's zone and then wet scrubber is utilised over them.

Lee et al. [49] claimed that gas and particles had six times more chance to contact collection device in the novel system [49]. It is being reported that particle collection efficiency is increased with the decrease in plate angle and increase in the pressure at scrubber nozzle tip.

Performance comparisons for different types of options available for gas cleaning are given in Table 4 [86].

Different technologies are suitable for different type of application and have added advantage over other e.g. cyclones are very efficient in removal of coarse particles whereas fail to remove PM10 and PM2.5.

Some of the technologies e.g. filters require high maintenance whereas wet scrubbers need chemical treatment for slurry

**Table 4**
Comparison of various technologies for gas cleaning [modified 86].

| Type of Technologies | Effectiveness (coarse particles) (%) | Removal efficiency (PM10) (%) | Removal efficiency (PM2.5) (%) | Indicative capitol cost | Indicative maintenance cost | Achievable final PM emission g/GJ | Remarks |
|---|---|---|---|---|---|---|---|
| Cyclone | 90–99 | 80–90 | < 80 | Least expensive | Least Expensive | 30 | Less effective for small particles |
| Multi-cyclone | 90–99 | 90–99 | < 80 | Least expensive | Least Expensive | 30 | Less effective for small particles |
| ESP | > 99 | > 99 | 80–90 | High | Medium high | 15 | Removal efficiency may be low for small plant |
| Fabric Filter | > 99 | > 99 | > 99 | Medium high | Medium high | < 15 | Final emission should be much less |
| Ceramic Filter | > 99 | > 99 | > 99 | High | Medium high | < 15 | Final emission should be much less |
| Mop Fan | > 95 | > 95 | > 95 | Medium | Low | < 25 | Technology need to be tested more for validity, also removes water soluble gas |
| Hybrid | > 99 | > 99 | > 99 | Medium to High | Medium | < 15 | Novel technology are more niche and problem specific |

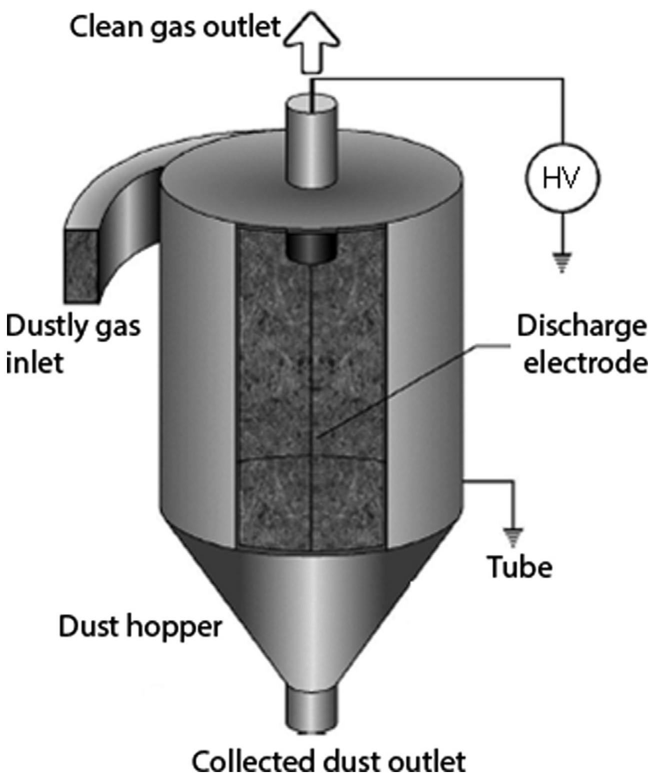


**Fig. 9.** Elecltrically engergized cyclone (electrocyclone) [60].

collected from flue gas cleaning. Both methods are more efficient for fine particles PM10 and PM2.5.

### 5.4. Removal of water solvable gas and mercury

Water soluble gases can be removed effectively either by wet methods or dry absorption. In dry scrubber's, excess of chemicals are required to achieve high removal efficiency. However in wet scrubbers normally requires special treatment of waste water. Typical water soluble gases from biomass boilers are sulphur dioxide ($SO_2$), ammonia ($NH_3$), hydrochloric acid (HCl) and hydrofluoric acid (HF). There are some other water soluble gases also exits but their concentration is very low. Both the methods have their merit and disadvantage e.g. wet methods always give some waste liquid while dry methods give dry residue. Waste treatment for wet methods can be fairly complex. But in some cases use of wet methods is having advantage e.g. chemicals can be re-used e.g. gypsum which can reduce cost.

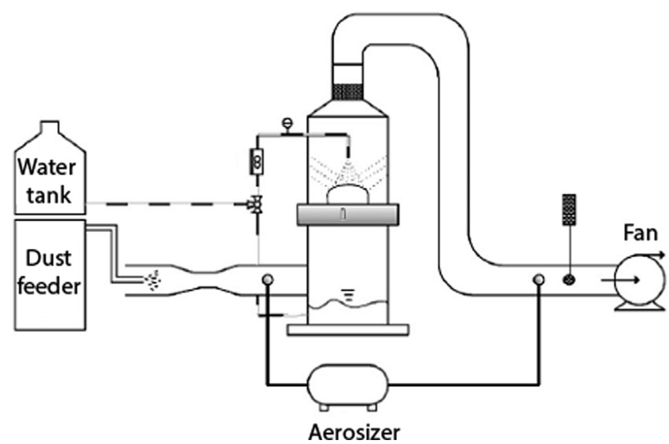


**Fig. 10.** Schematic of system using novel swirl cyclone scrubber [49].

The mercury is a highly toxic substance to humans, ecosystems and wildlife; high doses can be fatal, but even relatively low doses can damage the nervous system [87]. It is being reported that three mercury (Hg) type contaminations [87] can occur in combustion of biomass (i) gaseous elemental mercury (GEM), (ii) gaseous oxidised mercury (GOM), and (iii) fine particulate-bound mercury ($PBM_{2.5}$). A peculiar characteristic of mercury is that, it exists in the environment in a number of different chemical and physical forms, each with different behaviour in terms of transport and environmental effects [88]. Various directives and legislation controls the use and presence of Hg e.g. IPCC Directive controls use of Hg in chlor-akali industry and Directive 91/157/EEC limits use of Hg in batteries and accumulators. The EU-directive for mercury (Hg) and its compounds demands a maximum emission of 50 $\mu g/m^3$ for plants burning waste which is still very high. Recent methods for removal of mercury adopted introduction of powdered activated carbon sorbents into flue gas [89]. However these activated carbon materials are very costly and new alternative methods of using industrial waste [89] e.g. brominated ash has been proposed.

## 6. Discussions

Different methods of flue gas cleaning have been reported in literature. However still none of the method is most suitable for

use in domestic biomass applications. Filter based flue gas cleaning is more appropriate as it meets the demand of government regulation though high cost and maintenance worked as inhibitor for technology to be used by mass. Filters based technologies need replacement of certain parts of the system and require high maintenance cost though provide excellent performance. Wet scrubber based flue gas cleaning is another suitable option but comes with added responsibility of slurry treatment. These technologies might be suitable for biomass application at industrial level where different level of treatment can be used, however the scenario in residential building sector is completely different. Also cyclones are low in cost and maintenance and having added advantage over wet scrubber as they do not utilise any solvent. Other technologies like ESP are more efficient in removal of coarse particle as well as PM10 and PM2.5; however they are more expensive and are not good solution for small scale biomass combustion application. In recent years many hybrid technologies e.g. MOP fan, electrocyclone, etc. also been proposed and is being used for cleaning of gas and have demonstrated the added benefits with much better performance.

## 7. Conclusions

It is evident that application of biomass is restricted in residential sector due to particulate matters emissions. There is need to develop some novel solution of low cost and low maintenance targeted for residential biomass market. The study provided comprehensive idea about cleaning of gas from biomass combustion and reflected that it is difficult to obtain high efficiency for smaller particle range. The particle removal efficiency specially for PM2.5 is usually low (around 80%) for conventional cleaning devices. Different used technology for the cleaning has potential to achieve reduction in contamination; however hybrid solutions are much more efficient with comparison to other solutions. Many new hybrid methods employing more than one fundamental principle of contamination cleaning are much better and possess added advantage over conventional methods.

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